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Year: 2010

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DOI: <https://doi.org/10.1088/0954-3899/37/7A/075021>

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ZORA URL: <https://doi.org/10.5167/uzh-46052>

Journal Article

Accepted Version

Originally published at:

Amsler, C; Gutsche, T; Spanier, S; Törnqvist, N A (2010). Note on scalar mesons (Revised April 2010).

Journal of Physics G: Nuclear and Particle Physics, 37(7A):630-637.

DOI: <https://doi.org/10.1088/0954-3899/37/7A/075021>

## NOTE ON SCALAR MESONS

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**I. Introduction:** The scalar mesons are especially important to understand because they have the same quantum numbers as the vacuum ( $J^{PC} = 0^{++}$ ). Therefore they can condense into the vacuum and break a symmetry such as a global chiral  $U(N_f) \times U(N_f)$ . The details of how this symmetry breaking is implemented in Nature is one of the most profound problems in particle physics.

In contrast to the vector and tensor mesons, the identification of the scalar mesons is a long-standing puzzle. Scalar resonances are difficult to resolve because of their large decay widths which cause a strong overlap between resonances and background, and also because several decay channels open up within a short mass interval. In addition, the  $K\bar{K}$  and  $\eta\eta$  thresholds produce sharp cusps in the energy dependence of the resonant amplitude. Furthermore, one expects non- $q\bar{q}$  scalar objects, like glueballs and multiquark states in the mass range below 1800 MeV. For some recent reviews see Ref. [1–4].

Scalars are produced, for example, in  $\pi N$  scattering on polarized/unpolarized targets,  $p\bar{p}$  annihilation, central hadronic production,  $J/\Psi$ ,  $B$ -,  $D$ - and  $K$ -meson decays,  $\gamma\gamma$  formation, and  $\phi$  radiative decays. Experiments are accompanied by the development of theoretical models for the reaction amplitudes, which are based on common fundamental principles of two-body unitarity, analyticity, Lorentz invariance, and chiral- and flavor-symmetry using different techniques ( $K$ -matrix formalism,  $N/D$ -method, Dalitz Tuan ansatz, unitarized quark models with coupled channels, effective chiral field theories such as the linear sigma model, *etc.*). Dynamics near the lowest two-body thresholds in some analyses is described by crossed channel ( $t$ ,  $u$ ) meson exchange or with an effective range parameterization instead of or in addition to resonant features in the  $s$ -channel, only. Furthermore, elastic  $S$ -wave scattering amplitudes involving soft pions have zeros close to threshold [5–6], which may be shifted or removed in associated production processes.

The mass and width of a resonance are found from the position of the nearest pole in the process amplitude ( $T$ -matrix or  $S$ -matrix) at an unphysical sheet of the complex energy plane:  $(E - i\Gamma/2)$ . It is important to note that only in the case of narrow well-separated resonances, far away from the opening of decay channels, does the naive Breit-Wigner parameterization (or  $K$ -matrix pole parameterization) agree with this pole position.

In this note, we discuss all light scalars organized in the listings under the entries ( $I = 1/2$ )  $K_0^*(800)$  (or  $\kappa$ ),  $K_0^*(1430)$ , ( $I = 1$ )  $a_0(980)$ ,  $a_0(1450)$ , and ( $I = 0$ )  $f_0(600)$  (or  $\sigma$ ),  $f_0(980)$ ,  $f_0(1370)$ , and  $f_0(1500)$ . This list is minimal and does not necessarily exhaust the list of actual resonances. The ( $I = 2$ )  $\pi\pi$  and ( $I = 3/2$ )  $K\pi$  phase shifts do not exhibit any resonant behavior. See also our notes in previous issues for further comments on *e.g.*, scattering lengths and older papers.

**II. The  $I = 1/2$  States:** The  $K_0^*(1430)$  [7] is perhaps the least controversial of the light scalar mesons. The  $K\pi$   $S$ -wave scattering has two possible isospin channels,  $I = 1/2$  and  $I = 3/2$ . The  $I = 3/2$  wave is elastic and repulsive up to 1.7 GeV [8] and contains no known resonances. The  $I = 1/2$   $K\pi$  phase shift, measured from about 100 MeV above threshold in  $Kp$  production, rises smoothly, passes  $90^\circ$  at 1350 MeV, and continues to rise to about  $170^\circ$  at 1600 MeV. The first important inelastic threshold is  $K\eta'(958)$ . In the inelastic region the continuation of the amplitude is uncertain since the partial-wave decomposition has several solutions. The data are extrapolated towards the  $K\pi$  threshold using effective range type formulas [7,9], or chiral perturbation predictions [10–12]. In analyses using unitarized amplitudes there is agreement on the presence of a resonance pole around 1410 MeV having a width of about 300 MeV. With reduced model dependence [13] finds a larger width of 500 MeV.

The presence and properties of the light  $K^*(800)$  or “ $\kappa$ ” meson in the 700-900 MeV region are difficult to establish since it appears to have a very large width ( $\Gamma \approx 500$  MeV) and resides close to the  $K\pi$  threshold. Hadronic  $D$ -meson decays provide additional data points in the vicinity of the  $K\pi$

threshold - experimental results from E791 *e.g.* Ref. [14,15], FOCUS [13,16], CLEO [17], and BaBar [18] are discussed in the *Review of Charm Dalitz Plot Analyses*. Precision information from semileptonic  $D$  decays avoiding theoretically ambiguous three-body final state interactions is not available. BES II [19] (re-analyzed by [20]) finds a  $\kappa$  like structure in  $J/\psi$  decays to  $\bar{K}^{*0}(892)K^+\pi^-$  where  $\kappa$  recoils against the  $K^*(892)$ . Also clean with respect to final state interaction is the decay  $\tau^- \rightarrow K_S^0 \pi^- \nu_\tau$  studied by Belle [21], with  $K^*(800)$  parameters fixed to Ref. [19].

Some authors find a  $\kappa$  pole in their phenomenological analysis (see *e.g.* [11,17,22–34]), while others do not (see *e.g.* [12,18,35–37]). The pole position for the  $\kappa$  was found in a theoretical analysis [38] in the  $K\pi \rightarrow K\pi$  amplitude on the second sheet. This analysis involves the Mandelstam representation, which includes unitarity, analyticity and crossing symmetry.

**III. The  $I = 1$  States:** Two isovector states are known, the established  $a_0(980)$  and the  $a_0(1450)$ . Independent of any model, the  $K\bar{K}$  component in the  $a_0(980)$  wave function must be large: it lies just below the opening of the  $K\bar{K}$  channel to which it strongly couples. This generates an important cusp-like behavior in the resonant amplitude. Hence, its mass and width parameters are strongly distorted. To reveal its true coupling constants, a coupled channel model with energy-dependent widths and mass shift contributions is necessary. All listed  $a_0(980)$  measurements agree on a mass position value near 980 MeV, but the width takes values between 50 and 100 MeV, mostly due to the different models. For example, the analysis of the  $p\bar{p}$ -annihilation data [9] using an unitary  $K$ -matrix description finds a width as determined from the  $T$ -matrix pole of  $92 \pm 8$  MeV, while the observed width of the peak in the  $\pi\eta$  mass spectrum is about 45 MeV.

The relative coupling  $K\bar{K}/\pi\eta$  is determined indirectly from  $f_1(1285)$  [39–41] or  $\eta(1410)$  decays [42–44], from the line shape observed in the  $\pi\eta$  decay mode [45–48], or from the coupled-channel analysis of  $\pi\pi\eta$  and  $K\bar{K}\pi$  final states of  $p\bar{p}$  annihilation at rest [9].

The  $a_0(1450)$  is seen in  $p\bar{p}$  annihilation experiments with stopped and higher momenta  $\bar{p}$ , with a mass of about 1450 MeV or close to the  $a_2(1320)$  meson which is typically a dominant feature. A contribution from  $a_0(1450)$  is also found in the analysis of the  $D^\pm \rightarrow K^+ K^- \pi^\pm$  decay [49]. The broad structure at about 1300 MeV observed in  $\pi N \rightarrow K \bar{K} N$  reactions [50] needs further confirmation in its existence and isospin assignment.

**IV. The  $I = 0$  States:** The  $I = 0 J^{PC} = 0^{++}$  sector is the most complex one, both experimentally and theoretically. The data have been obtained from  $\pi\pi$ ,  $K\bar{K}$ ,  $\eta\eta$ ,  $4\pi$ , and  $\eta\eta'(958)$  systems produced in  $S$ -wave. Analyses based on several different production processes conclude that probably four poles are needed in the mass range from  $\pi\pi$  threshold to about 1600 MeV. The claimed isoscalar resonances are found under separate entries  $\sigma$  or  $f_0(600)$ ,  $f_0(980)$ ,  $f_0(1370)$ , and  $f_0(1500)$ .

For discussions of the  $\pi\pi$   $S$  wave below the  $K\bar{K}$  threshold and on the long history of the  $\sigma(600)$ , which was suggested in linear sigma models more than 50 years ago, see our reviews in previous editions and the conference proceedings [51].

Information on the  $\pi\pi$   $S$ -wave phase shift  $\delta_J^I = \delta_0^0$  was already extracted 35 years ago from the  $\pi N$  scattering [52,53], and near threshold from the  $K_{e4}$ -decay [54]. The reported  $\pi\pi \rightarrow K\bar{K}$  cross sections [55–58] have large uncertainties. The  $\pi N$  data have been analyzed in combination with high-statistics data (see entries labeled as RVUE for re-analyses of the data). The  $2\pi^0$  invariant mass spectra of the  $p\bar{p}$  annihilation at rest [59,60] and the central collision [61] do not show a distinct resonance structure below 900 MeV, but these data are consistently described with the standard solution for  $\pi N$  data [52,62], which allows for the existence of the broad  $\sigma$ . An enhancement is observed in the  $\pi^+\pi^-$  invariant mass near threshold in the decays  $D^+ \rightarrow \pi^+\pi^-\pi^+$  [63–65] and  $J/\psi \rightarrow \omega\pi^+\pi^-$  [66,67], and in  $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$  with very limited phase space [68,69].

The precise  $\sigma$  pole is difficult to establish because of its large width, and because it can certainly not be modelled by a naive Breit-Wigner resonance. It is distorted by background

as required by chiral symmetry, and from crossed channel exchanges, the  $f_0(1370)$ , and other dynamical features. However, most of the analyzes under  $f_0(600)$  listed in our previous issues agree on a pole position near  $(500 - i 250 \text{ MeV})$ . In particular, analyses of  $\pi\pi$  data that include unitarity,  $\pi\pi$  threshold behavior and the chiral symmetry constraints from Adler zeroes and scattering lengths need the  $\sigma$ .

A precise pole position with an uncertainty of less than 20 MeV (see our table for  $T$ -matrix pole) is derived by Ref. [70]. An important ingredient is the use of Roy-Steiner equations derived from crossing symmetry, analyticity and unitarity. With these constraints [70] find that their position of the  $\sigma$  pole depends, almost exclusively, only on the value of the isosinglet  $S$ -wave phase shift at 800 MeV and the  $S$ -wave scattering lengths  $a_0^0$  and  $a_0^2$ . Using analyticity and unitarity only to describe data from  $K_{2\pi}$  and  $K_{e4}$  decays [71] find comparable pole position and scattering length  $a_0^0$ . A similar determination in a fit by [72] to  $K_{e4}$  decay data and to higher energy  $\pi\pi$  phase shifts also results in a  $\sigma$  pole position consistent with the result of [70].

According to Ref. [73,74] the data for  $\sigma \rightarrow \gamma\gamma$  are consistent with what is expected for a two step process of  $\gamma\gamma \rightarrow \pi^+\pi^-$  via pion exchange in the  $t$ - and  $u$ -channel, followed by a final state interaction  $\pi^+\pi^- \rightarrow \pi^0\pi^0$ . The same conclusion is drawn in Ref. [75] where the bulk part of the  $\sigma \rightarrow \gamma\gamma$  decay width is dominated by rescattering. Therefore it may be difficult to learn anything new about the nature of the  $\sigma$  from its  $\gamma\gamma$  coupling. There are theoretical indications (*e.g.* [76–79]) that the  $\sigma$  pole behaves differently from a  $q\bar{q}$ -state.

The  $f_0(980)$  overlaps strongly with the  $\sigma$  and background represented by a very slowly varying phase extending to higher masses and/or the  $f_0(1370)$ . This can lead to a dip in the  $\pi\pi$  spectrum at the  $K\bar{K}$  threshold. It changes from a dip into a peak structure in the  $\pi^0\pi^0$  invariant mass spectrum of the reaction  $\pi^-p \rightarrow \pi^0\pi^0n$  [80], with increasing four-momentum transfer to the  $\pi^0\pi^0$  system, which means increasing the  $a_1$ -exchange contribution in the amplitude, while the  $\pi$ -exchange decreases. The  $\sigma$ , and the  $f_0(980)$ , are also observed in data for

radiative decays ( $\phi \rightarrow f_0 \gamma$ ) from SND [81,82], CMD2 [83], and KLOE [84,85]. Analyses of  $\gamma\gamma \rightarrow \pi\pi$  data [86–88] underline the importance of the  $K\bar{K}$  coupling of  $f_0(980)$ , while the resulting two-photon width of the  $f_0(980)$  cannot be determined precisely [89]. A reliable interpretation of the  $f_0(980)$  based on these observations is not possible at present.

**The  $f_0$ ’s above 1 GeV.** A meson resonance that is very well studied experimentally, is the  $f_0(1500)$  seen by the Crystal Barrel experiment in five decay modes:  $\pi\pi$ ,  $K\bar{K}$ ,  $\eta\eta$ ,  $\eta\eta'(958)$ , and  $4\pi$  [9,59,60]. Due to its interference with the  $f_0(1370)$  (and  $f_0(1710)$ ), the peak attributed to  $f_0(1500)$  can appear shifted in invariant mass spectra. Therefore, the application of simple Breit-Wigner forms arrive at slightly different resonance masses for  $f_0(1500)$ . Analyses of central-production data of the likewise five decay modes Ref. [90,91] agree on the description of the  $S$ -wave with the one above. The  $p\bar{p}$ ,  $p\bar{n}/n\bar{p}$  measurements [92–94,60] show a single enhancement at 1400 MeV in the invariant  $4\pi$  mass spectra, which is resolved into  $f_0(1370)$  and  $f_0(1500)$  [95,96]. The data on  $4\pi$  from central production [97] require both resonances, too, but disagree on the relative content of  $\rho\rho$  and  $\sigma\sigma$  in  $4\pi$ . All investigations agree that the  $4\pi$  decay mode represents about half of the  $f_0(1500)$  decay width and is dominant for  $f_0(1370)$ .

The determination of the  $\pi\pi$  coupling of  $f_0(1370)$  is aggravated by the strong overlap with the broad  $f_0(600)$  and  $f_0(1500)$ . Since it does not show up prominently in the  $2\pi$  spectra, its mass and width are difficult to determine. Multichannel analyses of hadronically produced two- and three-body final states agree on a mass between 1300 MeV and 1400 MeV and a narrow  $f_0(1500)$ , but arrive at a somewhat smaller width for  $f_0(1370)$ .

Both Belle and BaBar have observed scalars in  $B$  and  $D$  meson decays. They observe broad or narrow structures between 1 and 1.6 GeV in  $K^+K^-$  and  $\pi^+\pi^-$  decays [98–102] (see also [103]). It could be a result of interference of several resonances in this mass range, but lack of statistics prevents an unambiguous identification of this effect.

**V. Interpretation of the scalars below 1 GeV:** In the literature, many suggestions are discussed, such as conventional  $q\bar{q}$  mesons,  $q\bar{q}q\bar{q}$  or meson-meson bound states mixed with a scalar glueball. In reality, they can be superpositions of these components, and one depends on models to determine the dominant one. Although we have seen progress in recent years, this question remains open. Here, we mention some of the present conclusions.

The  $f_0(980)$  and  $a_0(980)$  are often interpreted as multiquark states [104–108] or  $K\bar{K}$  bound states [109]. The insight into their internal structure using two-photon widths [82,110–115] is not conclusive. The  $f_0(980)$  appears as a peak structure in  $J/\psi \rightarrow \phi\pi^+\pi^-$  and in  $D_s$  decays without  $f_0(600)$  background. Based on that observation it is suggested that  $f_0(980)$  has a large  $s\bar{s}$  component, which according to Ref. [116] is surrounded by a virtual  $K\bar{K}$  cloud (see also [117]). Data on radiative decays ( $\phi \rightarrow f_0\gamma$  and  $\phi \rightarrow a_0\gamma$ ) from SND, CMD2, and KLOE (see above) favor a 4-quark picture of the  $f_0(980)$  and  $a_0(980)$ . The underlying model for this conclusion [118,119] however may be oversimplified. But it remains quite possible that the states  $f_0(980)$  and  $a_0(980)$ , together with the  $f_0(600)$  and the  $K_0^*(800)$ , form a new low-mass state nonet of predominantly four-quark states, where at larger distances the quarks recombine into a pair of pseudoscalar mesons creating a meson cloud (see e.g. Ref. [120]). Different QCD sum rule studies [121–125] do not agree on a tetraquark configuration for the same particle group.

Attempts have been made to start directly from chiral Lagrangians [24,119,126–130] which predict the existence of the  $\sigma$  meson near 500 MeV. Hence, e.g., in the chiral linear sigma model with 3 flavors, the  $\sigma$ ,  $a_0(980)$ ,  $f_0(980)$ , and  $\kappa$  (or  $K_0^*(1430)$ ) would form a nonet (not necessarily  $q\bar{q}$ ), while the lightest pseudoscalars would be their chiral partners.

In such models inspired by the linear sigma model the light  $\sigma(600)$  is often referred to as the "Higgs boson of strong interactions", since the  $\sigma$  plays a role similar to the Higgs particle in electro-weak symmetry breaking. It is important for chiral symmetry breaking which generates most of the proton



and  $\eta'$  mass, and what is referred to as the constituent quark mass.

In the approach of Ref. [24] the above resonances are generated starting from chiral perturbation theory predictions near the first open channel, and then by extending the predictions to the resonance regions using unitarity.

In the unitarized quark model with coupled  $q\bar{q}$  and meson-meson channels, the light scalars can be understood as additional manifestations of bare  $q\bar{q}$  confinement states, strongly mass shifted from the 1.3 - 1.5 GeV region and very distorted due to the strong  $^3P_0$  coupling to  $S$ -wave two-meson decay channels [131–135]. Thus, the light scalar nonet comprising the  $f_0(600)$ ,  $f_0(980)$ ,  $K_0^*(800)$ , and  $a_0(980)$ , as well as the regular nonet consisting of the  $f_0(1370)$ ,  $f_0(1500)$  (or  $f_0(1700)$ ),  $K_0^*(1430)$ , and  $a_0(1450)$ , respectively, are two manifestations of the same bare input states (see also Ref. [136]) .

Other models with different groupings of the observed resonances exist and may *e.g.* be found in earlier versions of this review and papers listed as other related papers below.

## ***VI. Interpretation of the $f_0$ 's above 1 GeV:***

The  $f_0(1370)$  and  $f_0(1500)$  decay mostly into pions ( $2\pi$  and  $4\pi$ ) while the  $f_0(1710)$  decays mainly into  $K\bar{K}$  final states. The  $K\bar{K}$  decay branching ratio of the  $f_0(1500)$  is small [90,137].

If one uses the naive quark model it is natural to assume that the  $f_0(1370)$ ,  $a_0(1450)$ , and the  $K_0^*(1430)$  are in the same SU(3) flavor nonet, being the  $(u\bar{u} + d\bar{d})$ ,  $u\bar{d}$  and  $u\bar{s}$  states, respectively, while the  $f_0(1710)$  is the  $s\bar{s}$  state. Indeed, the production of  $f_0(1710)$  (and  $f_2'(1525)$ ) is observed in  $p\bar{p}$  annihilation [138] but the rate is suppressed compared to  $f_0(1500)$  (respectively  $f_2(1270)$ ), as would be expected from the OZI rule for  $s\bar{s}$  states. The  $f_0(1500)$  would also qualify as  $(u\bar{u} + d\bar{d})$  state, although it is very narrow compared to the other states and too light to be the first radial excitation.

However, in  $\gamma\gamma$  collisions leading to  $K_S^0 K_S^0$  [139] a spin 0 signal is observed at the  $f_0(1710)$  mass (together with a dominant spin 2 component), while the  $f_0(1500)$  is not observed in  $\gamma\gamma \rightarrow K\bar{K}$  nor  $\pi^+\pi^-$  [140]. In  $\gamma\gamma$  collisions leading to  $\pi^0\pi^0$  Ref. [141] reports the observation of a scalar around 1470 MeV

albeit with large uncertainties on the mass and  $\gamma\gamma$  couplings. This state could be the  $f_0(1370)$  or the  $f_0(1500)$ . The upper limit from  $\pi^+\pi^-$  [140] excludes a large  $n\bar{n}$  content for the  $f_0(1500)$  and hence points to a mainly  $s\bar{s}$  state [142]. This appears to contradict the small  $K\bar{K}$  decay branching ratio of the  $f_0(1500)$  and makes a  $q\bar{q}$  assignment difficult for this state. Hence the  $f_0(1500)$  could be mainly glue due the absence of a  $2\gamma$ -coupling, while the  $f_0(1710)$  coupling to  $2\gamma$  would be compatible with an  $s\bar{s}$  state. However, the  $2\gamma$ -couplings are sensitive to glue mixing with  $q\bar{q}$  [143].

Note that an isovector scalar, possibly the  $a_0(1450)$  (albeit at a lower mass of 1317 MeV) is observed in  $\gamma\gamma$  collisions leading to  $\eta\pi^0$  [144]. The state interferes destructively with the non-resonant background, but its  $\gamma\gamma$  coupling is comparable to that of the  $a_2(1320)$ , in accord with simple predictions (see *e.g.* Ref. [142]) .

The narrow width of  $f_0(1500)$ , and its enhanced production at low transverse momentum transfer in central collisions [145–147] also favor  $f_0(1500)$  to be non- $q\bar{q}$ . In the mixing scheme of Ref. [143], which uses central production data from WA102 and the recent hadronic  $J/\psi$  decay data from BES [148,149], glue is shared between  $f_0(1370)$ ,  $f_0(1500)$  and  $f_0(1710)$ . The  $f_0(1370)$  is mainly  $n\bar{n}$ , the  $f_0(1500)$  mainly glue and the  $f_0(1710)$  dominantly  $s\bar{s}$ . This agrees with previous analyses [150,151].

However, alternative schemes have been proposed (*e.g.* in Ref. [152,153]; for a review see *e.g.* Ref. [1]) . In particular, for a scalar glueball, the two-gluon coupling to  $n\bar{n}$  appears to be suppressed by chiral symmetry [154] and therefore the  $K\bar{K}$  decay could be enhanced. This mechanism would imply that the  $f_0(1710)$  can possibly be interpreted as an unmixed glueball [155]. In Ref. [156] the large  $K^+K^-$  scalar signal reported by Belle in  $B$  decays into  $KK\bar{K}$  [157], compatible with the  $f_0(1500)$ , is explained as due to constructive interference with a broad glueball background. However, the Belle data are inconsistent with the BaBar measurements which show instead a broad scalar at this mass for  $B$  decays into both  $K^\pm K^\pm K^\mp$  [101] and  $K^+K^-\pi^0$  [158].

Whether the  $f_0(1500)$  is observed in ‘gluon rich’ radiative  $J/\psi$  decays is debatable [159] because of the limited amount of data - more data for this and the  $\gamma\gamma$  mode are needed.

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